

Supermassive Black Hole Research in the Post-HST Era

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Abstract.

Thanks to its unprecedented spatial resolution, the Hubble Space Telescope has ended a 20-year long stalemate by detecting the dynamical signature of nuclear supermassive black holes (SBHs) in a sizeable number of nearby galaxies. These detections have revealed the existence of a symbiotic relationship between SBHs and their hosts, changing the way we view SBH and galaxy formation. In this contribution I review which are the most pressing outstanding issues in SBH research, and what are the technological requirements needed to address them.

1. The Current Status of SBH Searches

The study of supermassive black holes is one of the areas of modern astrophysics which has benefited most from the launch of HST. After two decades of tantalizing but inconclusive ground-based studies, the HST/FOS observations of M87 (Harms et al. 1994) and NGC 4261 (Ferrarese et al. 1996) provided the first firm measurements of SBH masses in galactic nuclei. In the years that followed, FOS and STIS data lead to detections in ten additional galaxies (Bower et al. 1998; van der Marel & van den Bosch 1998; Ferrarese & Ford 1999; Emsellem et al. 1999; Cretton & van den Bosh 1999; Verdoes Kleijn et al. 2000; Gebhardt et al. 2000a; Joseph et al. 2001; Barth et al. 2001; Sarzi et al. 2001). The superiority of HST over ground based facilities in this field is easily understood. Only dynamical evidence, either from gas or stellar kinematics, can yield compelling proof of the existence of SBHs. With rare exceptions (e.g. M31, M87), ground based telescopes lack the spatial resolution necessary to resolve the SBH “sphere of influence”, i.e. the region of space within which the SBH gravitational influence dominates that of the surrounding stars:

$$r_h = GM_\bullet/\sigma^2 \sim 11.2(M_\bullet/10^8 M_\odot)/(\sigma/200 \text{ km s}^{-1})^2 \text{ pc}, \quad (1)$$

with σ the stellar velocity dispersion and M_\bullet the SBH mass. Resolving r_h is a necessary condition for a SBH detection to be made; not meeting it leads to spurious detections and biased masses (Merritt & Ferrarese 2001a).

With over a dozen secure measurements, it has become possible to search for correlations between M_\bullet and the overall properties of the host galaxies. The first relation to emerge was one between M_\bullet and the blue luminosity L_B of the surrounding bulge (Kormendy & Richstone 1995). A much tighter correlation

was subsequently discovered between M_\bullet and the bulge stellar velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000b):

$$M_\bullet = \beta \left(\frac{\sigma}{200 \text{ km s}^{-1}} \right)^\alpha. \quad (2)$$

with $\alpha = 4.58 \pm 0.52$ and $\beta = (1.66 \pm 0.32) \times 10^8 \text{ M}_\odot$ (Ferrarese 2002a). More recently, evidence has emerged that a fundamental relation might exist between M_\bullet and the mass M_{DM} of the dark matter halos in which the SBHs presumably formed (Ferrarese 2002b):

$$\frac{M_\bullet}{10^8 \text{ M}_\odot} \sim 0.10 \left(\frac{M_{DM}}{10^{12} \text{ M}_\odot} \right)^{1.65} \quad (3)$$

The above relations have proven invaluable in the study of SBH demographics (Merritt & Ferrarese 2001b; Ferrarese 2002a; Yu & Tremaine 2002) and have generated intense activity on the theoretical front (Haehnelt, Natarajan & Rees 1998; Silk & Rees 1998; Cattaneo, Haehnelt & Rees 1999; Adams, Graff & Richstone 2000; Monaco et al. 2000; Haehnelt & Kauffmann 2000; Wyithe & Loeb 2002). At the same time, new questions have arisen, and with them the need for further observational constraints. In this contribution, I will address three such questions, and identify the technological requirements necessary to answer them.

- *What are the characteristics of the $M_\bullet - \sigma$ relation? Does the slope and/or normalization of the relation depend on Hubble type, environment, and/or redshift?* As theoretical models are refined, tighter observational constraints will be required. Most of the SBHs detected to date are in the $10^8 \lesssim M_\bullet \lesssim 10^9$ range. The $M_\bullet - \sigma$ relation is not sampled below 10^6 M_\odot , and badly sampled for $10^6 \lesssim M_\bullet \lesssim 10^7 \text{ M}_\odot$. There are few spiral galaxies represented, all of which are early type, and only two galaxies well beyond 30 Mpc.
- *Are binary supermassive black holes long lived?* The existence and lifespan of binary SBHs can have dramatic consequences, from shaping the morphology and dynamics of the resulting galaxy (Milosavljevic & Merritt 2001; Milosavljevic et al. 2002; Ravindranath et al. 2002; Yu 2002) to destroying nuclear dark matter halo cusps (Merritt et al. 2002).
- *How small can nuclear BHs be? Are there nuclear BHs in globular clusters?* There is no dynamical evidence for “intermediate mass” black holes (IBHs) in the $M_\bullet \sim 10^2 - 10^6 \text{ M}_\odot$ range, although their existence in the off-nuclear regions of some starburst galaxies is supported by energetic arguments (Fabbiano et al. 2001; Matsumoto et al. 2001). There is also no dynamical evidence that BHs are formed in the nuclei of globular clusters (van der Marel et al. 2000; Gebhardt et al. 2000). However, whether such black holes exist is critical for our understanding of how SBHs form. In “top-down” self-regulating models that trace the formation of SBHs to the very early stages of galaxy formation, there is a natural lower limit of $\sim 10^6 \text{ M}_\odot$ to M_\bullet (e.g. Loeb 1993; Silk & Rees 1998; Haehnelt, Natarajan &

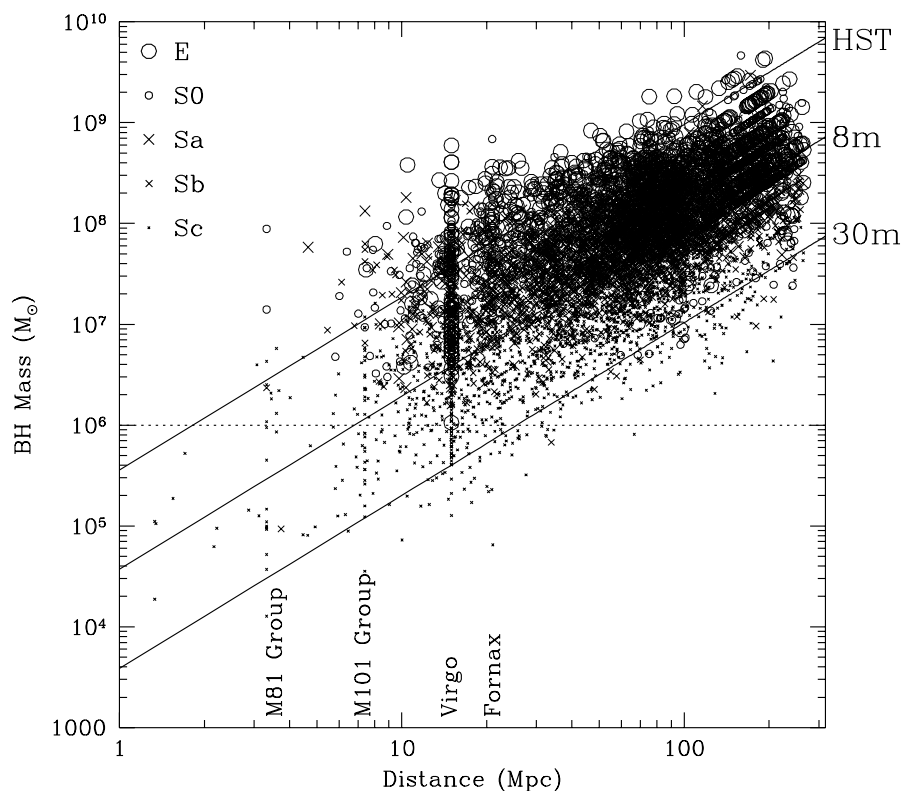


Figure 1. SBH mass vs. distance for all galaxies in the CfA Redshift Sample (Huchra et al. 1990). Only for the galaxies which lie above the solid lines the sphere of influence of the putative nuclear SBH can be resolved by HST/STIS, an 8m and a 30m diffraction limited telescope. A few nearby groups and clusters are marked. It should be noted that because of the large scatter in the $M_{\bullet} - L_B$ relation (a factor of several in M_{\bullet}), this figure has only statistical value.

Rees 1998). On the other hand, in “bottom-up” models nuclear SBHs are formed by the merging of IBHs. These are deposited at the galactic center as the globular clusters in which they originally formed spiral in due to dynamical friction (Portegies Zwart & McMillan 2002; Ebisuzaki et al. 2001). In the latter scenario, no physical reason would prevent the formation of SBHs with $M_{\bullet} \lesssim 10^6 M_{\odot}$.

2. Building the Local Sample

Galaxies come in all flavors, but do all flavors come with a SBH? The sample of galaxies within the reach of HST is remarkably homogeneous. Most are early type galaxies. And although we might expect the number of detections to double or perhaps even triple as new HST data become available (Kormendy & Gebhardt 2001), most will remain in the $10^8 \lesssim M_{\bullet} \lesssim 10^9 M_{\odot}$ range which is

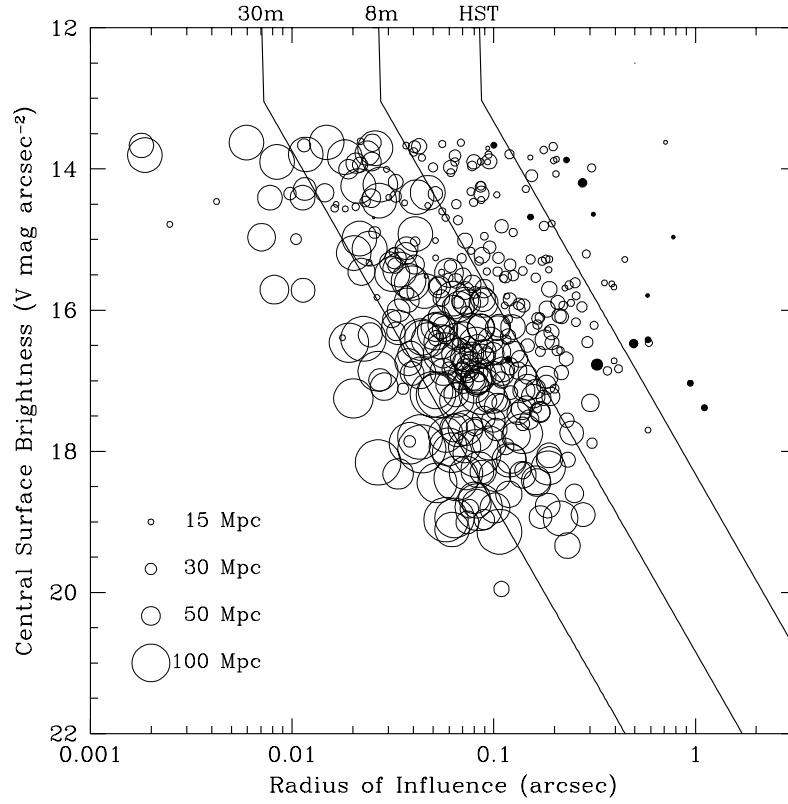


Figure 2. SBH radius of influence vs. central surface brightness for the Early Type galaxy sample of Faber et al. (1989). The size of the symbols is proportional to the galaxy distances, as shown in the legend. Spectra with ideal signal-to-noise and spatial resolution for dynamical studies can be collected in the equivalent of 3 HST orbits only for the galaxies to the right of the solid lines (shown for HST/STIS, an 8m and a 30m diffraction limited telescopes). The solid circles identify galaxies observed with HST.

already well sampled by the current data (Merritt & Ferrarese 2002a). Hopes of breaking the $10^6 M_\odot$ barrier lie in one galaxy only, NGC 205, a compact elliptical already scheduled to be observed with HST (P.I. L. Ferrarese)¹.

But there are other barriers HST cannot break. The low central surface brightness which characterizes giant ellipticals (e.g. Ferrarese et al. 1994; Lauer et al. 1995; Rest et al. 2000) makes stellar dynamical studies with HST prohibitive. For instance, measuring M_\bullet in M87 ($d \sim 15$ Mpc) using stellar dynamics would require over 100 orbits of STIS time². While this problem can be avoided by using gas, rather than stellar, kinematics, only a fraction of ellipticals host the regular NGC4261-like dust disks (Jaffe et al. 1993) which make

¹Based on the $M_\bullet - \sigma$ relation, NGC 205 is expected to host a $\sim 7.5 \times 10^4 M_\odot$ black hole; at a distance of 740 kpc, a black hole as small as $6 \times 10^4 M_\odot$ can be detected by STIS.

gas dynamical studies possible. Therefore, ironically, most of the very largest SBHs ($M_{\bullet} \gtrsim 10^9 M_{\odot}$) are beyond the reach of HST.

Similarly, the vast majority of dwarf elliptical galaxies are beyond HST capabilities. Assuming that the $M_{\bullet} - \sigma$ relation holds in the $\sigma \sim \text{a few } \times 10 \text{ km s}^{-1}$ regime that characterizes these objects, the sphere of influence of the putative SBH at their centers is accessible only in the most nearby systems. In these cases, the stellar population is resolved into individual stars, each too faint to be handled by HST's small mirror. For instance, a constraint on the central mass in NGC 147 ($d \sim 660 \text{ kpc}$) would require several hundred orbits with STIS. The situation for late type spirals is no better. The upper limit on M_{\bullet} in M33, the closest Sc galaxy, puts the sphere of influence of the putative BH a factor ~ 20 below the resolution capabilities of HST.

The above statements are quantified in Figure 1. For each galaxy in the CfA redshift sample (Huchra et al. 1990), M_{\bullet} is calculated from the $M_{\bullet} - L_B$ relation given by Ferrarese & Merritt (2000), after a correction suitable to each Hubble type is applied to convert total luminosity to bulge luminosity (Fukugita et al. 1998). If only resolution constraints are considered, most late type spirals (Sb - Sc) are expected to host SBHs too small to be resolved by HST. Only a handful of SAs are within reach. It is only with an 8m class telescope that a complete sample of galaxies spanning the whole Hubble sequence can be collected. Even then, little would be gained below $10^6 M_{\odot}$: pushing this limit down by an order of magnitude requires a 30m diffraction limited telescope.

The above constraints become tighter when exposure time requirements are folded in. Figure 2 shows the detection limits for HST, an 8m and a 30m diffraction limited telescopes assuming the equivalent of 3 HST orbits of integration on each galaxy². The points represent the early type galaxy sample of Faber et al. (1989), with M_{\bullet} calculated using the $M_{\bullet} - \sigma$ relation. Again, HST can only see the top of the iceberg, producing enough SBH detections to allow us a glimpse of what lays underneath, but leaving most of the parameter space unexplored. To study the influence of environment on the formation and evolution of SBHs, it would be helpful to probe Coma and the most nearby rich Abell clusters at $d \sim 100 \text{ Mpc}$. In order to push farther and perhaps study the redshift evolution of the $M_{\bullet} - \sigma$ relation, reverberation mapping (see Brad Peterson's contribution in these proceedings) will likely remain the only viable method.

3. Binary Supermassive Black Holes

The formation of binary SBHs as a consequence of merging seems unavoidable (Begelman, Blandford & Rees 1980), however the evolution of the SBH binary after merging is very uncertain (Ebisuzaki, Makino & Okumura 1991; Milosavljevic & Merritt 2002; Yu 2002). The recent work of Milosavljevic & Merritt (2002) represents the state of the art in numerical simulations of merging galaxies with SBHs. We will adopt the results of this work to estimate the resolution requirements necessary to detect the dynamical signature of a SBH binary. Milosavljevic & Merritt follow the merging of two low-luminosity ellip-

²The calculation assumes S/N=50 at $\sim 8500 \text{ \AA}$.

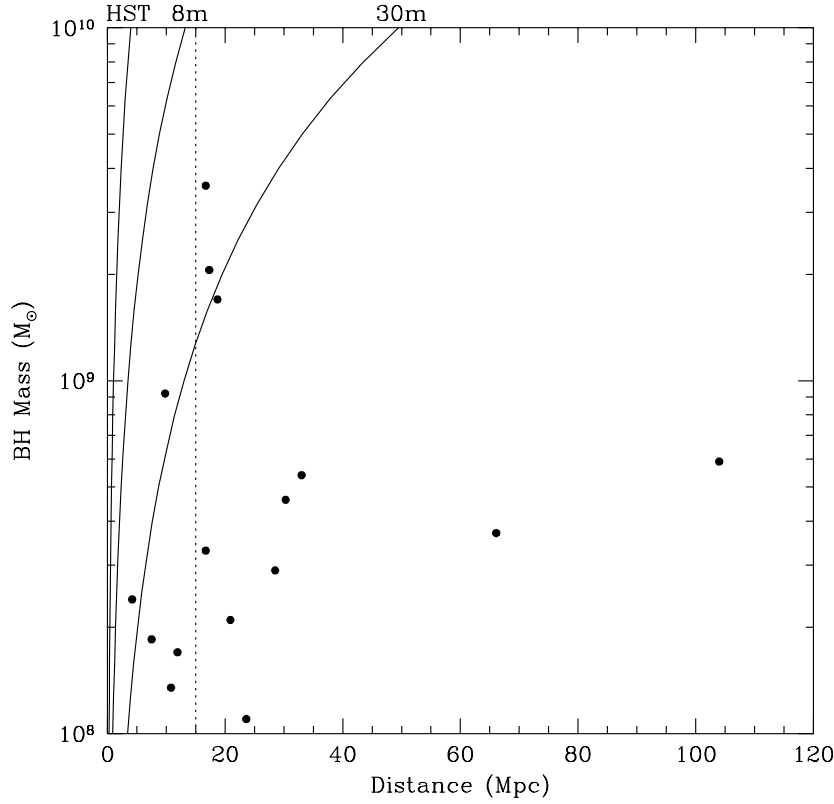


Figure 3. The points represent all SBH masses detected to date (see references in Merritt & Ferrarese 2000). According to the simulations of Milosavljevic & Merritt 2001, a SBH would have to lie to the left of the solid line (drawn for HST, an 8m and a 30m diffraction limited telescope) to be resolved as a binary. The vertical dotted line marks the position of the Virgo cluster.

ticals, characterized by steep power-law stellar density profiles. Well within one Myr after the galaxies merge, the two SBHs form a hard binary with separation between a few hundredths to a few parsecs, depending on the SBHs masses. By exchanging energy with nearby stars, the binary will start to harden; however, Milosavljevic & Merritt find that the hardening will eventually stall, as a consequence of the depletion of stars with which the binary can interact. At this stage, the separation between the SBHs is $\lesssim 0.2$ pc ($\propto M_{\bullet}^{0.57}$), and the stellar rotational velocity and velocity dispersion differ significantly from the single SBH case (see Fig. 15 of Milosavljevic & Merritt). Figure 3 shows the limit at which the “final” distance between the binary SBHs can be resolved with HST, an 8m and a 30m diffraction limited telescope, as a function of the binary mass and distance. The solid points show all SBHs detected to date. Rather obviously, a direct dynamical detection of a binary SBH would require a 30m class telescope, and even then only a few of the most nearby galaxies would be accessible. Unless proof of the existence of binary SBHs can be obtained in some

other way (with LISA, for instance), it would not be a bad idea to start cheering for OWL (see the contribution by Roberto Gilmozzi in these proceedings).

4. Black Holes in Globular Clusters

The formation of BHs at the centers of highly concentrated globular clusters (GCs) is suggested by theoretical arguments and numerical simulations (Miller & Hamilton 2001; Mouri & Taniguchi 2002; Portegies Zwart & McMillan 2002). Detecting the signature of a BH in GCs is best done through proper motion, rather than spectroscopic studies. The latter have been pursued in the case of M15, with no conclusive results (van der Marel 2000; Gebhardt et al. 2000). Velocities of several tens to several hundred stars within the sphere of influence of the putative BH must be collected in order to derive an accurate value of the velocity dispersion; unfortunately at the Mg b triplet ($\sim 5500 \text{ \AA}$), and even more severely at the Ca II triplet ($\sim 8500 \text{ \AA}$), the fainter turnoff and main sequence stars are drowned in the light of a few nearby giants. In the case of M15, for instance, the sphere of influence of a $10^3 M_\odot$ BH is $\sim 1''$, and about 90 velocities are needed to produce a value of the velocity dispersion accurate to 10% within this region; using state of the art ground-based instrumentation, Gebhardt et al. (2000) were able to measure velocities for only 5 stars within $1''$.

The suitability of proper motion studies in constraining the central potential has been demonstrated in spectacular fashion for the Galactic center (Ghez et al. 2000; Genzel et al. 2000), using ground based facilities. With HST, the art of extracting astrometric information from WFPC2 images has been perfected by Anderson & King (2000), who can reach an astonishing 0.005 pixel positional accuracy using properly dithered data. Constraints on the BH mass at the center of Galactic globular clusters can be easily calculated; under appropriate assumptions, with two ten-orbit exposures, taken one year apart, HST could set limits of $2000 M_\odot$ or better on the BH masses at the center of \sim ten of the nearest Galactic GCs. For a few GCs, the limit is below $1000 M_\odot$, well in the range of BH masses estimated for the off-nuclear IBHs in the Antennae galaxies and M82 (Fabbiano et al. 2001; Matsumoto et al. 2001). While even tighter constraints could be reached using a larger aperture, the combination of HST and ACS can be very competitive.

Table 1 summarized the observational requirements needed to answer the questions posed in the introduction of this contribution. While most applications will require higher spatial resolution and a larger collective area, the detection of BHs in GCs could indeed be the next legacy of HST to SBH research.

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Table 1. Technical Requirements

Project: Enlarging the Sample and Probing $< 10^6$ and $> 10^9 M_\odot$ SBHs					
<i>Needed to study systematics, distinguish between “bottom-up” and “top-down” models of SBH formation, constrain the role of feedback in SBH accretion during merging</i>					
Resolution	Aperture	FOV	λ range	$\lambda/\Delta\lambda$	Comments
$< 0''.02$	$> 8\text{m}$	$\text{few} \times 10''$	5500–9500 Å	10,000	Longslit IFU highly desirable
Project: Resolving SBH Binaries					
<i>Needed to constrain dynamical models of galaxy mergers, determine the impact of SBH binaries in the morphological evolution of galaxies, constrain accretion mechanism.</i>					
Resolution	Aperture	FOV	λ range	$\lambda/\Delta\lambda$	Comments
$< 0''.007$	$> 30\text{m}$	$\text{few} \times 10''$	$> 8000 \text{ Å}$	10,000	IFU
Project: Detecting BHs in GCs					
<i>Needed to constrain dynamical models for SBH evolution, investigate the connection between GCs, nuclear SBHs, and galactic bulges.</i>					
Resolution	Aperture	FOV	λ range	$\lambda/\Delta\lambda$	Comments
$< 0''.05$	$> 2.5\text{m}$	$\text{few} \times 10''$	U or B -band	N/A	High Resolution Imager, High Dynamic Range

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